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Environmental Assessment of Freight Transportation in the U.S.

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Abstract

Goal, Scope and Background. This study provides a life-cycle inventory of air emissions (CO_2, NO_x, PM_{10}, and CO) associated with the transportation of goods by road, rail, and air in the U.S. It includes the manufacturing, use, maintenance, and end-of-life (EOL) of vehicles, the construction, operation, maintenance, and EOL of transportation infrastructure, as well as oil exploration, fuel refining, and fuel distribution.

Methods. The comparison is performed using hybrid life-cycle assessment (LCA), a combination of process-based LCA and economic input-output analysis-based LCA (EIO-LCA). Results are summed by means of a common functional unit of grams of air pollutant per ton-mile of freight activity.

Results and Discussion. Results show that the vehicle use phase is responsible for approximately 70% of total emissions of CO_2 for all three modes. This confirms that tailpipe emissions underestimate total emissions of freight transportation as infrastructure, pre-combustion, as well as vehicle manufacturing and EOL account for a sizeable share of total emissions. Depending on mode and pollutant, differences between tailpipe emissions and total systemwide emissions can range from only 4% for road transportation's CO emissions to an almost tenfold difference for air transportation's PM_{10} emissions.

Conclusion. Rail freight has the lowest associated air emissions, followed by road and air transportation. Depending on the pollutant, rail is 50–94% less polluting than road. Air transportation is rated the least efficient in terms of air emissions, partly due to the fact that it carries low weight cargo. It emits 35 times more CO_2 than rail and 18 times more than road transportation on a ton-mile basis. It is important to consider infrastructure, vehicle manufacturing, and pre-combustion processes, whose life-cycle share is likely to increase as new tailpipe emission standards are enforced.

Recommendation and Outlook. Emission factors, fuel efficiency, and equipment utilization contribute the most to uncertainty in the results. Further studies are necessary to address all variables that influence these parameters, such as road grade, vehicle speed, and vehicle weight. A focus on regional variation, EOL processes, fuel refining processes, terminals, as well as more accurate infrastructure allocation between freight and passenger transportation would strengthen the model.

Keywords: Air transportation; environment; freight transportation; life-cycle assessment; life-cycle inventory; rail transportation; road transportation; transportation infrastructure; United States

Introduction

A comprehensive life-cycle inventory of road, rail, and air freight transportation in the U.S. has not yet been published. Additionally, most life-cycle studies of various products and services rely on transportation emission factors that are outdated and incomplete. They are usually limited to tailpipe emissions, disregarding the production and EOL of vehicles, the provision of infrastructure, and upstream processes associated with the fuel life-cycle (e.g., petroleum exploration, refining, and distribution of fuel). The life-cycle inventory included in this study enables the calculation of emission factors that account for these elements.

Freight activity is estimated to grow by 100–200% in the south of the U.S., and 79% in the northeast between 2000 and 2020 (OECD 2001). Air and road transportation will experience the highest growth (USDOT 2005). International freight volumes are also expected to grow at faster rates than domestic traffic, and U.S. ports and border gateways will likely experience gridlock.

Competition among modes will become more intense as transportation capacity becomes more constrained. Investment in new capacity usually relies on purely economic considerations, but governmental policies at some point will require such investments to account for environmental criteria. It is of paramount importance that such environmental analyses assume a life-cycle perspective to encompass all life-cycle stages of vehicles, infrastructure, and fuels.

There have been few life-cycle environmental studies comparing different modes of freight transportation. Spielmann (2005) has provided the most complete and comprehensive life-cycle inventory so far of road, rail, and water transportation of goods in Europe, including all life-cycle phases of vehicles, infrastructure, and fuels. Marheineke (1998) performed a hybrid life-cycle assessment (LCA) for road freight transportation in Germany, analyzing the production, use, and disposal of trucks, as well as the construction and maintenance of roads. In the U.S., Stodolsky (1998) compared life-cycle energy use and air emissions of trucks and freight trains, finding that rail is about three times more efficient than road in terms of energy use and emissions. However, the analysis did not include the EOL of vehicles or the provision of infrastructure.

1 Scope of Work

This study compares CO_2, NO_x, PM_{10}, and CO emissions from road, rail, and air transportation of goods in the continental U.S. The framework (**Table 1**) ensures that all life-cycle phases of vehicles, transportation infrastructure, and fuels are taken into account.

Even though regional differences exist, this study takes a national perspective. The types of vehicles utilized are relatively standard across the country, with differences only arising from additional fuel consumption due to mountainous terrain and extreme weather conditions (e.g., the use of air conditioning and heating systems). Construction standards for infrastructure are also geographically uniform for the most part (Horvath 1998), but maintenance can vary due to additional repairs necessary from temperature fluctuations throughout the day or year (e.g., in snowy or desert locations), deicing operations at airports, snow plowing, and rail weed control.

This analysis evaluates the degree of competitiveness among the three modes in terms of their environmental performance. Since short and medium-distance transportation rely almost entirely on trucking, long-distance continental transportation is emphasized to enable the comparison of road, rail and air transportation. A similar analogy implies the exclusion of intercontinental shipping, which relies on maritime shipping with the exception of time-sensitive cargo transported by air. Inland shipping is excluded due to its limited geographical coverage in the U.S. (e.g., mostly along the Midwest-South corridor on the Mississippi River).

The first and last miles are not included since they are similar for all three modes. All modes require transloading (e.g., transfer between equipment) at the beginning and at the end. While this might not be true for road shipments (e.g., large trucks might be used along the entire corridor), the goal of this study is to provide better mode-specific numbers that will be utilized in more detailed, corridor specific analyses where more than one mode is used.

The study does not differentiate between commodities since it is based on national statistics that bundle all products and consider an average shipment for each mode. The main influence of commodity is on mode choice since, e.g., rail is not typically used for high-value commodities, and air is not sensible for bulk goods. Vehicle utilization can be adjusted in the model to account for commodities on the extreme ends of the density scale.

Air emissions are measured per ton-mile. This brings the advantage of a clear comparison among modes, as well as the ability to compare this study with previous analyses that used similar metrics (ton-km for European studies). Such functional unit tends to underestimate rail impacts while overestimating air impacts, given that rail and air usually carry heavy and light cargo, respectively. Therefore, a similar analysis could be done with respect to value of goods, which better represents benefits to the economy.

Table 1: Scope of work

		Road	Rail	Air
Geographical Scope		Continental United States		
Functional Unit		Ton-mile		
Inventory Assessment		Emissions of CO_2, NO_x, PM_{10}, and CO		
Impact Assessment		Excluded from analysis		
Vehicle Life-cycle Phase	Manufacturing	• Manufacturing of heavy-duty diesel truck (tractor and 53' dry van)	• Manufacturing of diesel locomotive and general purpose railcars	• Manufacturing of aircraft
	Use	• Truck tailpipe emissions (including idling) • Truck maintenance (including tires)	• Locomotive emissions • Switching operations • Train maintenance	• Aircraft emissions • Aircraft maintenance
	EOL	Dismantling, shredding, separation, and disposal of materials		
Infrastructure Life-cycle Phase	Construction	• Interstate highway construction	• Rail track construction	• Runway construction • Airport cargo terminal construction
	Use	• Interstate highway maintenance	• Rail track maintenance	• Runway maintenance • Airport operations (electricity, deicing) • Airport maintenance
	EOL	• Recycling or disposal of materials	• Not included	• Recycling or disposal of runway materials • Decommissioning of terminals not included
Fuel Life-cycle Phase	Manufacturing	Petroleum refining and distribution		
	Use	Included in vehicle use		
	EOL	No EOL phase		

The analysis includes the manufacturing, use, and maintenance of vehicles (tractor, trailer, locomotive, railcar, and aircraft), construction, operation, and maintenance of infrastructure (interstate roads, rest stops, rail tracks, rail yards, airport terminals, and runways), and exploration, refining, distribution, and use of fuels (diesel and jet fuel). The EOL phase (recycling and disposal) of selected elements is also included in the analysis. Since the first and last legs of a trip are not included, cross-docking facilities (road-road) and intermodal terminals (road-rail) are excluded from the scope of work. Rail yards are included as rail cars are frequently shifted during marshalling operations. Due to the air network's hub and spoke configuration, many flights are not direct and demand cargo handling operations at airport cargo terminals. This justifies its inclusion in the analysis.

All transportation components (vehicles, infrastructure, fuels) are assumed to be manufactured in the U.S., which enabled the use of the U.S. economic input-output (I-O) model in the study. This is especially reasonable for transportation infrastructure, since raw materials come mostly from North America. Even though the same assumption holds true for vehicles, a large share of vehicle components comes from other countries (Facanha 2005). This becomes an issue as other countries might use different production technologies, energy mixes, and distribution systems, including international shipping. With respect to fuel processes, most refining occurs in the U.S. but more than half of the U.S. crude oil is imported. This does not constitute a problem since I-O accounts for international shipping as an economic input to refineries.

Based on each vehicle's and infrastructure's lifetime, total incurred freight activity (measured in ton-miles) is calculated. Total impacts associated with each component are then divided by the total freight activity during its lifetime. This enables the model to add the impacts from different components under a common unit. For example, pavements are assumed to have a lifetime of 10 years. By dividing the total environmental effects associated with the construction of pavements by the freight activity of 10 years, the environmental burden from pavement construction can be calculated in terms of emissions per ton-mile.

Since infrastructure is shared between passenger and freight transportation, allocation rules are set. Rail infrastructure is assumed to be 100% dedicated to freight, as only Class I rail statistics are considered. Road infrastructure (the interstate highway system) is 40% allocated to freight, the share of damage incurred to roads that is expected to come from trucks (March 1998). Allocation of air infrastructure is done on the basis of landed weight.

2 Methodology – Life-cycle Assessment

The environmental effects of road, rail, and air freight transportation in the U.S. are evaluated and quantified by means of an LCA. There are primarily two LCA methodologies: a process-based LCA, and the economic input-output analysis-based LCA (EIO-LCA). A hybrid LCA model combines elements of both methodologies, and is the selected tool for this study.

In process-based LCA, the user maps all processes associated with all life-cycle phases of a product, and associates inputs (e.g., energy, water) and outputs (e.g., air emissions, noise, water discharges, accidents) with each process. By doing so, the total environmental load can be determined. Although this model enables very specific analyses, its heavy data requirements may make it time consuming and costly, especially when attempts are made to include suppliers upstream in the supply chain. Due to great flexibility in designing system boundaries, the comparison of two LCAs of the same product is not always straightforward.

In order to overcome some of the issues posed by process-based LCA (e.g., data requirements, boundary selection), EIO-LCA was created (Hendrickson 1998). It couples environmental data with the economic I-O model, and can determine the environmental load associated with the production of commodities (products and services). For example, $10,000 worth of motor vehicles is associated with environmental metrics (e.g., energy use and air pollution). As the economic I-O model determines the interdependencies among different economic sectors, the effects of the supply chain (e.g., production of steel for a motor vehicle) are included. This model can provide comprehensive and industry-wide environmental analyses, but it may not include the level of detail found in a well-executed process-based LCA, especially when the studied commodity falls into a sector that is broadly defined. The latest EIO-LCA (2005) model is based on 1997 data, requiring all economic inputs to be converted into 1997 U.S. dollars according to sector-specific producer price indices from the U.S. Department of Labor (2005).

A variety of issues arise when performing an LCA of transportation, the first one being that transportation is a service utilizing vehicles, infrastructure, and fuels. The complexity found in each of these components justifies the use of a hybrid methodology. A hybrid LCA model combines the advantages of both process-based LCA and EIO-LCA. Since the quantity and quality of process information varies widely, it is understandable that process-based LCA alone cannot perform a complete LCA of transportation. By the same token, the aggregation of economic sectors in EIO-LCA enables its use for only a limited number of analysis components. Additionally, EIO-LCA only includes the production of commodities, so the use and EOL phases must be accounted for separately by either process-based LCA or alternate economic sectors in EIO-LCA. Suh and Huppes (2005) compared six methods for life-cycle inventories, including three types of hybrid approaches, while pointing to the advantages of using hybrid methodologies. Suh et al. (2004) analyzed the issues involved in boundary selection when utilizing hybrid approaches in life-cycle inventories.

Table 2 illustrates the methodology used for each component. Even though research has shown that different types of fuel (diesel v. jet fuel) require different processes within a refinery (Wang 2004), data are usually bundled and do not

Table 2: LCA methodology used in each component

	Component	Production	Use / Operation	Maintenance	EOL
Road	Tractor	E	P	E / P	P
	Trailer	E	P	E / P	P
	Road	P	P	P	P
Rail	Locomotive	E	P	E	P
	Railcar	E	P	E	P
	Rail track	E / P	E	E	–
Air	Aircraft	E	P	E	P
	Runway	P	P	P	P
	Cargo terminal	E	E	E	–
Fuel Upstream		E / P	–	–	–

E: EIO-LCA; P: Process-based LCA

enable differentiation amongst fuels. The remaining elements of the table are divided by transportation mode.

Total emissions (**Eq. 1**) of a given pollutant associated with a transportation mode are expressed by the sum of different components (e.g., vehicle use, infrastructure construction, fuel refining):

$$T = \sum_{i=1}^{n} \frac{I_i}{A_i} * E_i * f \tag{1}$$

where

T = Total emissions of given pollutant (mass pollutant / ton-miles)
n = Total number of components
I_i = Input (gallons, US$, energy, or amount of production material)
A_i = Freight activity associated with component (ton-miles)
E_i = Emission factor (mass of pollutant / I_i input units)
f = Share of input allocated to freight

Input values (I_i) can be of economic nature in the case of components assessed through EIO-LCA. For example, the production cost of a heavy-duty diesel truck is used as the input for truck manufacturing. For process-based LCA components, input values take units of either gallons of fuel, energy (e.g., MJ), or mass of a given material (e.g., cement, bitumen). Emission factors always assume units comparable to input values. For example, all emission factors in EIO-LCA assume units of mass of pollutant per economic value.

Freight activity is associated with the lifetime of the input. For example, if the inputs are truck maintenance expenditures incurred in one year, the annual freight activity must be calculated. For locomotive production, the cost incurred in manufacturing a locomotive is used as the input, while the freight activity needs to account for the lifetime of a locomotive. Freight activity can be calculated in two ways: it is either the product of total tonnage incurred in a given time period by the average shipment distance, or the product of total distance traveled in a given time period by the average shipment weight. In the case of vehicle use, the term (I_i / A_i) is obtained by inverting the product of the average shipment weight and fuel efficiency. The average shipment weight can be calculated via **Eq. 2**.

$$\overline{W} = C * U * (1 - M) \tag{2}$$

where

$\overline{W}$ = Average shipment weight (tons)
C = Vehicle capacity (tons)
U = Vehicle utilization (%)
M = Empty miles (%)

2.1 Road transportation

Road transportation is responsible for over half of all freight revenue generated even though it accounts for only 28% of all ton-miles (BTS 2004). This is due to an increasing shift from basic goods, e.g., coal, which is mainly transported by rail, to higher value shipments such as electronic components. Time-sensitive and high-inventory cost shipments can afford more expensive transportation rates to guarantee faster and more reliable transit times which road transportation can provide. As a reference, road transportation is almost 12 times more expensive than rail (in revenue per ton-miles).

2.1.1 Truck manufacturing

The study is limited to Class 7 and 8 trucks (gross vehicle weights over 33,000 lb) due to the focus on long-distance transportation that enables competition with rail and air modes. Additionally, dry vans are emphasized due to the general nature of the cargo they hold. Trucks are broken down into two modules: a 3-axle truck tractor and a 2-axle trailer, which is normally 40, 48, or 53-feet long. The study focuses on the 53' long trailer due to its high capacity that is becoming prevalent in the long distance market.

The manufacturing of both tractor and trailer is evaluated through EIO-LCA as the sectors 'Heavy duty truck manufacturing' and 'Truck trailer manufacturing' are specific enough to provide reliable estimates of the associated environmental burden. Economic inputs are taken from the Federal Highway Administration, which provides prices for different types of equipment (USDOT 1995). Vehicle costs are calculated by assuming a 10% sales markup on truck prices.

In order to estimate the economic input per ton-mile, it is necessary to determine total freight activity (in ton-miles) associated with the lifetime of a tractor and a trailer. The EPA (1997a) reckons that a truck can run for 290,000 miles, while a trailer is assumed to have a lifetime of 60% of the

tractor's lifetime. The payload capacity for a 53' trailer is 49.1 tons, which is assumed to be used at 75% of capacity, and run empty on 25% of the distance it travels (USDOT 1995). These elements are combined to calculate the average shipment size according to Eq. 2.

2.1.2 Truck maintenance

Vehicle maintenance includes tire maintenance, general repairs to exhaust system, engine, transmission, exterior paint, body, windows, wheel alignment, brake system, radiator, electrical components, fuel system, heating and air conditioning, lubrication, and inspection. The American Trucking Association (2003) provides average maintenance costs per mile, breaking them down in outside general maintenance and tires, which are assessed through EIO-LCA by the sectors 'Automotive repair and maintenance, except car washes' and 'Tire manufacturing', respectively. As the tire manufacturing sector accounts for just the production of tires, their distribution to wholesalers is analyzed separately by assuming 85% utilization of a delivery truck dedicated to tires that travels 200 miles. A heavy-duty diesel truck has 18 tires, which need to be replaced every 100,000 miles.

2.1.3 Truck tailpipe emissions

Truck tailpipe emissions are calculated using the U.S. Environmental Protection Agency's (EPA) emission factors (BTS 2004), which are converted from grams/bhp-hour to grams/gallon by assuming a diesel energy content of 139,000 BTU/gallon. Fuel efficiency (BTS 2004) and an average shipment size enable the subsequent conversion to grams/ton-mile. Truck idling, which accounts for the time spent in truck stops, represents an estimated 5 to 10% of total fuel consumed (CARB 2003).

2.1.4 Truck EOL

There is limited research on EOL processes of heavy-duty diesel trucks. Their fate is assumed to be comparable to the fate of a personal automobile, an area where data are more likely to be available. The availability of process-related data and emission factors enables the use of a process-based LCA for this component, which includes dismantling, shredding, material separation, landfill disposal, and associated transportation.

The dismantling process is critical as hazardous materials, fluids and batteries are banned from landfills according to current regulations (Keoleian 1997). Other parts are also salvaged due to their resale value (e.g., catalytic converters, alternators, starters, engines, clutches, water pumps). Larger aluminum, copper, and other nonferrous metal parts might also be separated and sold to specialized processors. The remaining parts, commonly referred to as the hulk, are usually compressed and flattened for easier transport. The hulk is assumed to make 75% of the weight of the original truck. Energy associated with the dismantling process is mostly human energy, thus excluded from this analysis.

After the hulk is transported from the dismantler to the shredder, it is shredded, and its ferrous fraction magnetically separated from the rest. Keoleian (1997) estimated that this process consumes 97 kJ/kg. The ferrous scrap consisting of iron and steel is then transported to a metal processor.

The nonferrous part of the shredded material consists of metals (e.g., aluminum, lead, copper, magnesium, zinc, brass, nickel), some entrained ferrous material, plastics, rubber, glass, and miscellaneous parts (Keoleian 1997). Nonferrous metals are collected by gravity separation, and usually sold to the nonferrous scrap market. The energy consumed by the separation process varies from 66 kJ/kg to 170 kJ/kg. In this analysis the average value is taken. The remaining parts that cannot be separated for recycling are sent to a landfill. Truck material composition and recyclable content for different materials are taken from Stodolsky (1998) and Keoleian (1997), respectively.

2.1.5 Road construction and maintenance

The study is limited to the interstate highway system as it carries 77% of all freight activity in the U.S. (BTS 1993). A 4-lane asphalt highway (2 lanes in each direction) is assumed as the national average, and road standards (e.g., lane and shoulder width, pavement design) are derived from AASHTO (1990). PaLATE (2004), a pavement LCA tool developed by the Consortium on Green Design and Manufacturing at the University of California, Berkeley is used to estimate the environmental effects of road construction and maintenance. PaLATE accounts for the production and transportation of raw materials to the construction site, the energy and emissions associated with road construction, as well as recycling and disposal of old pavement.

It is also necessary to estimate the life-cycle freight activity associated with the interstate highway system. PaLATE provides results in terms of total emissions, while historical data from 1960 to 1994, the period when most of the interstate highway system was built, give total ton-miles transported on the interstate highway system. Asphalt pavement is considered to have a lifetime of 10 years, and regular maintenance is assumed to include minor repairs and repatching. Annual maintenance requirements are assumed to be 1/10 of construction requirements.

Allocation is necessary as roads are shared between passenger and freight transportation. A study by March (1998) concluded that 40% of the damage to roads is due to freight traffic.

2.1.6 Road EOL

PaLATE accounts for recycling and disposal of old pavement. These results are bundled under road construction.

2.2 Rail transportation

Rail dominates the transportation freight market, accounting for 40% of all ton-miles transported in the U.S. (BTS 2004). Rail is responsible for the transportation of 70% of all automobiles, 30% of grain harvest, and 65% of coal in North America (AAR 2004). However, rail operating revenues account for less than 10% of total freight operating revenue due to the low value of the cargo hauled. Rail analysis herein is limited to Class I railways, which are responsible for the majority of freight haulage.

2.2.1 Train manufacturing and maintenance

According to the Association of American Railroads, AAR (2004), there is an average of 48.5 railcars per train. EIO-LCA is used to assess the manufacturing and maintenance of locomotives and railcars. The 'Railroad rolling stock manufacturing' sector, used to describe both components, is specific enough to justify its appropriate use.

Almost all rail freight traffic is moved by diesel locomotives in the U.S., which are of two major types: four and six-axle 'road switchers', ranging from 3,900 to 4,000 hp (Armstrong 1990). The average freight locomotive costs about $2 million (Myers 2005). There is a wide variety of railcars, but the focus here is on general purpose freight cars that can compete with road transportation in the long-distance market. The AAR (2004) reckons that an average freight car costs almost $50,000. A 10% sales markup is assumed for both locomotives and railcars.

To determine the economic input for locomotives and railcars in terms of ton-miles, it is necessary to determine the lifetime of each component, the average annual miles, and the average shipment weight per train. Lifetimes for locomotives and railcars are assumed to be 30 and 10 years, respectively. Average annual miles and shipment weight per train are determined from statistics collected by the BTS (2004) and AAR (2004). Economic inputs are divided by total life-cycle freight activity, and then input into EIO-LCA.

Maintenance costs are also assessed through EIO-LCA by the sector 'Other maintenance and repair construction'. Even though this is a relatively broad sector, maintenance is not expected to have a significant impact on total life-cycle emissions from locomotives and railcars. This is true given the industry's focus on emphasizing design changes to improve locomotive reliability and reduce maintenance (Armstrong 1990). The AAR (2004) publishes operating expenditures on equipment, which is assumed to be a good estimate of maintenance costs. This economic input is then divided by the annual average ton-miles with data collected from BTS (2004). Both figures are based on averages from 1960 to 2001 to provide a consistent comparison with the interstate highway system.

2.2.2 Locomotive emissions

Emissions from diesel locomotives are assessed through emission factors published by the EPA (1997b). The same conversion performed for truck emissions, from grams/bhp-hour to grams/mile, is done for locomotive emissions, assuming diesel energy content of 139,000 BTU/gallon (DOE 2002), and an average fuel efficiency of 0.14 miles/gallon (BTS 2004). The average shipment weight per train, as published by the AAR (2004) is used for the final conversion to grams/ton-mile.

Freight operations in rail yards are not captured by this method, and need to be considered separately. The EPA (1997b) estimates that 270 million gallons of diesel are consumed annually for switching operations. By combining this figure with specific emission factors for switching, the associated emissions are calculated.

2.2.3 Train EOL

Similarly to heavy-duty diesel trucks, the EOL of locomotives and railcars is assumed to consist of dismantling, shredding, separation, and disposal, already described under the truck EOL.

Aside from vehicle weight and material composition, all remaining assumptions follow the road transportation case. A General Electric Evolution series locomotive weighs 415,000 pounds (General Electric 2005), and its material composition is assumed to be 80% iron and steel, 10% other metals, and 10% other materials. An average railcar is assumed to weigh 50,000 pounds, and be made of 50% iron and steel, 45% aluminum, and 5% other materials.

2.2.4 Rail track construction and maintenance

A hybrid inventory approach is taken to evaluate the impacts of rail track construction, accounting for rails and crossties supported on two layers of ballast on top of a subbase (Esveld 1989). Different configurations have been tried, but the traditional rail-tie-ballast system has proved the most cost-effective (Armstrong 1990).

The top layer of ballast is made of crushed rock (granite, traprock, and selected hard stones), while the sub-ballast layer consists of pit-run gravel (Armstrong 1990). Both layers sit on top of a subbase composed of gravel. The construction and maintenance of these 3 layers are assessed through PaLATE. Steel and wood requirements, in terms of weight of material per mile, come from Armstrong (1990), and account for steel rails, spikes, steel tie plates, and treated wood crossties. Emissions from the production of both materials are evaluated in EIO-LCA with the sectors 'Iron and steel mills' and 'Sawmills', respectively. Economic inputs are derived from steel and wood market prices (USGS 1997, Wood Resources International 2003). Lifetimes for base, steel rail and wood ties are assumed to be 50, 50, and 25 years, respectively. Total freight activity faced by the rail track is based on the 1960–2001 average calculated from BTS (2004) data. The energy associated with the installation of rails and crossties and their transportation to the construction site are not included.

The AAR (2004) publishes rail operating expenses on 'ways and structures', which includes maintenance, operations, and new construction. To subtract new construction from this number, the amount of material utilized to lay new rail and crossties, also available from the AAR, is multiplied by material prices and subtracted from the original total. The resulting annual expenditures are then divided by the average ton-mileage from 1960–2001, and assessed through the 'Other maintenance and repair construction' sector in EIO-LCA.

The additional tracks necessary for switching operations in rail yards are included, but office buildings are left out for simplification purposes and because its impacts are expected to be minimal overall.

2.2.5 Rail track EOL

Because most rail tracks remain unutilized after being taken out of service, no EOL effects are assessed.

2.3 Air transportation

Airfreight has long been in the market for high-value commodities and emergency shipments. It is responsible for less than 1% of all freight activity in the U.S., measured in ton-miles (BTS 2004). Its importance however, should not be underestimated as it is responsible for 20% of all freight revenue generated.

2.3.1 Aircraft manufacturing and maintenance

According to Boeing (2005), they are responsible for 90% of the world's freight aircrafts, with virtually absolute dominance of the U.S. market. Boeing 747s are responsible for 50% of the world's airfreight capacity, therefore it is taken as the model aircraft for this study. It is assumed that the aircraft is 100% dedicated to freight. The environmental assessment of aircraft manufacturing is performed in EIO-LCA using the sector that bears the same name.

Boeing (2005) also provides other important data, such as the 747's price, capacity (tons), and lifetime (years). BTS (2004) provides the average distance per shipment (973 miles), which combined with an assumed number of weekly trips (6) and total number of years in service (lifetime of 20 years), can provide total life-cycle miles. Average shipment weight is determined by assuming 75% equipment utilization and 25% empty back haulage. By dividing total aircraft cost, assuming a 10% sales markup, by the product of life-cycle miles and average shipment weight, the economic input per ton-mile is determined.

Aircraft maintenance is assessed in EIO-LCA through the 'Other maintenance and repair construction' sector. Even though this sector is broad in nature, it is chosen for simplification purposes. The International Civil Aviation Organization (2002) publishes financial data for commercial air carriers. Maintenance expenditures from all dedicated airfreight companies are summed and divided by their respective ton-miles in 2002.

2.3.2 Aircraft emissions

Fuel consumption and emission data specific to the Boeing 747-400 are taken from IPCC (1996). Data for aircraft cruise cycle and landing/take-off are considered separately, and an average distance per flight and an average payload enable the conversion of fuel consumption and emission factors to an indicator per ton-mile. Aircraft idling is not included due to lack of data.

2.3.3 Aircraft EOL

The EOL of aircrafts is assumed to consist of dismantling, shredding, separation, and disposal, already described under truck EOL.

Aside from vehicle weight and material composition, all remaining assumptions follow the road transportation case. A Boeing 747-400 weighs approximately 285,000 pounds (Boeing 2005), and its material composition is 68% aluminum, 17% carbon reinforced polymers, 9% steel, 4% titanium, and 2% miscellaneous parts (Cantor 2001).

2.3.4 Airport construction

The modeling of an airport focuses on two major components: runways and terminal buildings. The environmental assessment of runways is analogous to road infrastructure, but accounting for the fact that runways are made of a combination of asphalt, concrete and reinforced steel. Terminal buildings are evaluated with EIO-LCA under the sector 'Commercial and institutional buildings'. Although this is a fairly broad sector, which is likely not to be completely representative of an airport terminal, the contribution of terminal construction is not very significant. Hence EIO-LCA is used for simplification purposes. The Seattle-Tacoma airport is taken as the model of an average U.S. airport as its annual cargo activity closely matches the national average.

Based on published data by the Port of Seattle (2005), it is assumed that 90% of total cargo terminal area is of warehouse-type construction, with the remaining 10% being office space. Construction costs per square foot are taken from R. S. Means (2002). In order to normalize construction costs per ton-mile, freight activity for an average airport is calculated by taking Seattle-Tacoma's cargo activity in tons (Port of Seattle 2005) and multiplying it by an air shipment's average distance (BTS 2004). This method ensures that emissions from both departing and arriving airports are considered.

Total runway requirements are taken from Port of Seattle (2005), including the cargo aircraft parking apron, and two runways. Standard widths for runways and shoulders are considered (Neufville 2003). Design standards (e.g., thickness of different layers) are taken from Bay (2000), who describes the pavement used in runway 16L-34R: a subgrade layer of gravel, a layer of portland cement concrete, as well as a top layer of asphalt concrete. PaLATE is used to calculate energy and emissions associated with the construction, maintenance, recycling, and disposal of pavements. Final input numbers are divided by total freight activity (ton-miles), calculated by the same method described for terminal buildings.

2.3.5 Airport operations and maintenance

Airport operations and maintenance consist of runway resurfacing, operation of airport facilities, traffic services, and snow and ice removal. The sector 'Power generation and supply' is used in EIO-LCA to assess the electricity consumed in airport operations. The freight share of the electricity budget for 2001 for the Seattle-Tacoma airport is allocated in proportion to passenger and cargo landed weight. Freight operations account for approximately 8%.

Runway resurfacing is included in the PaLATE calculations, while deicing is accounted for separately as Seattle-Tacoma does not perform such operations. Freight is again responsible for 8% of all deicing costs. The EPA (2000) published information regarding the total volume and cost of deicing fluid used in the U.S., which are combined with total airfreight activity to obtain an economic input per ton-mile. The analysis is performed in EIO-LCA using the sector 'Other miscellaneous chemical product manufacturing'.

2.3.6 Airport EOL

The recycling and disposal of pavements is already accounted for in runway construction and maintenance. The numbers were not made explicit due to their minimal impact when compared to construction and maintenance. Decommissioning of terminals is excluded due to its minimal impact on the final results.

2.4 Fuel refining and distribution

Upstream fuel processes are treated as mode-independent due to lack of data on different processes for each type of fuel. As the emission factors provided by the EPA only include emissions from fuel burning, upstream processes are not accounted for. These include, among others, oil exploration, refining, as well as fuel distribution from refineries to refueling stations. Oil exploration and diesel refining are accounted for by EIO-LCA through the 'Petroleum refineries' sector, while fuel distribution is analyzed by process-based LCA.

EIO-LCA ensures that all refining and upstream processes are included in the analysis. DOE (2005) provides diesel retail price ($/gallon). Taxes, marketing and distribution costs are deducted to determine the refiner's costs. This is then converted to $/mile through a fuel efficiency calculation. In order to determine the economic input per ton-mile, the average shipment weight is calculated by Eq. 2.

The distribution of fuel, not accounted for by EIO-LCA, is assessed separately. The transportation from the refineries to the bulk terminals is performed via pipelines (59%), barges (32.7%), and rail (8.3%) (Argonne 2001). Respective traveled distances are 400, 520, and 800 miles. The transportation from the bulk terminals to refueling stations is performed by a 4,000-gallon tanker, assumed to be 100% utilized, to travel 50 miles to a gas station, return empty to the bulk terminal, and have a fuel efficiency of 6.2 miles/gallon (BTS 2004). Total emissions associated with one trip are calculated using emission factors from the EPA (BTS 2004). The conversion of emissions per trip to emissions per ton-mile is done through the calculation of the number of ton-miles enabled by each equipment. Fuel efficiency is used in the conversion of gallons to miles, with the subsequent conversion to ton-miles using the average shipment weight.

3 Results and Discussion

Confirming most prior studies that compared rail and road, rail scored better than road for all four pollutants, being 50–94% less polluting than road, depending on the pollutant (**Fig. 1**). Air transportation is rated the least efficient in terms of air emissions, partly due to the fact that it carries low weight cargo. Air transportation emits 35 times more CO_2 than rail and 18 times more than road transportation on a ton-mile basis.

Life-cycle phases are divided into four categories. *Fuel combustion* includes emissions from the vehicle use phase, while *vehicle (without fuel combustion)* accounts for vehicle manufacturing, maintenance, and EOL. *Infrastructure* includes all processes associated with transportation infrastructure, accounting for construction, operations, maintenance, and EOL. *Precombustion* includes upstream fuel processes (i.e., oil exploration, refining, and fuel distribution).

Fuel combustion is the predominant life-cycle activity, in particular for CO_2 and NO_x. **Fig. 2** presents how each life-cycle phase contributes to CO_2 emissions for all three transportation modes. Fuel combustion is responsible for around 70% of total emissions. The study also points to the relatively high energy intensity associated with aircraft production (19% of the total) versus road and rail vehicle production (10%). For PM_{10}, infrastructure is an important source, 13% of the total emissions for rail, 28% for air, and 50% for road transportation.

One of the goals of this study is to demonstrate the importance of all life-cycle phases, not only fuel combustion. In **Fig. 3**, total emissions of the four air pollutants are compared to fuel combustion emissions, which are given a value of 1. In the road case, where fuel combustion emissions make up the largest share of emissions, the difference between tailpipe emissions and total emissions ranges from 4% for CO to 170% for PM_{10}. For rail, differences range from 6% for NO_x to 40% for CO_2. Emissions from air transportation operation considerably underestimate total emissions, with differences ranging from 34% for NO_x, 46% for CO_2, a 2.3-fold gap for CO, and an almost 10-fold gap for PM_{10}.

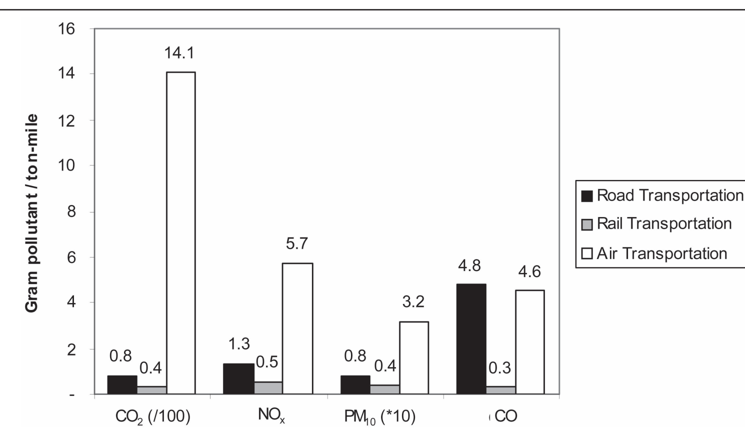

Fig. 1: Mode comparison

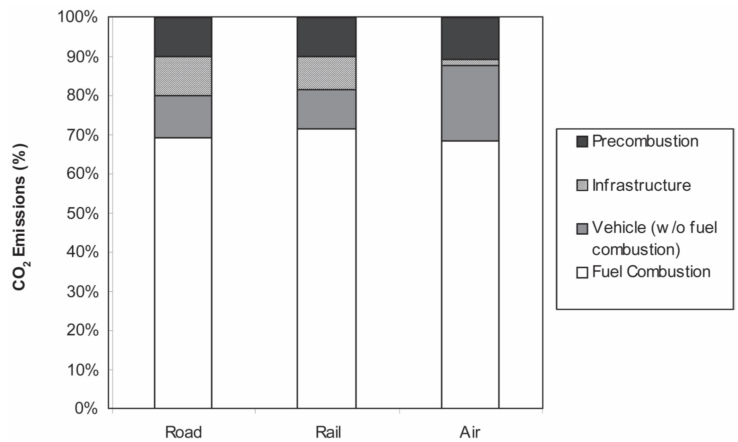

Fig. 2: Phase comparison

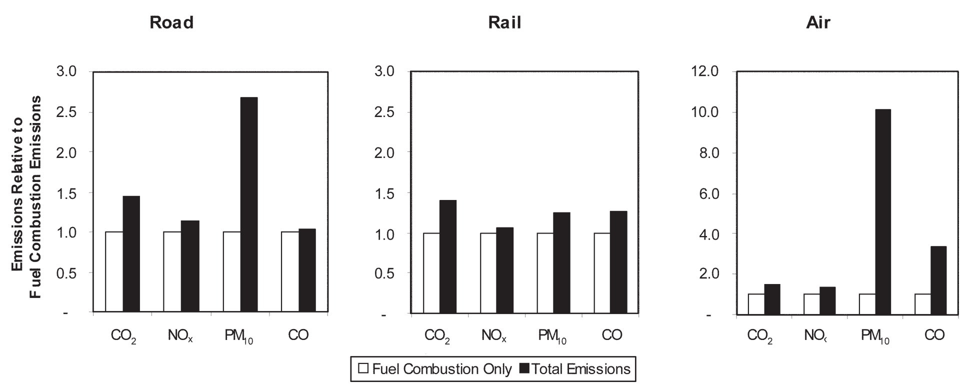

Fig. 3: Comparison between fuel combustion emissions and total emissions

3.1 Uncertainty Assessment

Huijbregts (1998) provides a framework for handling uncertainty in the development of LCAs, with the consideration of model, choice, and parameter uncertainty. Model and choice uncertainty are tackled qualitatively and include the definition of system boundaries, the selection of a functional unit, the design of process flows, the selection of the appropriate methodology for each part of the study, and the application of allocation procedures. Amongst the major issues are:

- Broad economic sectors in EIO-LCA: the values associated with each sector are an average across all enterprises that fall into that sector. If such enterprises have a wide range of production technologies and/or business practices, an average might not be representative. Examples are construction and maintenance sectors, which comprise a very broad variety of industries.
- Allocation: while rail transportation in the U.S. is predominantly freight-based, road and air infrastructure are shared among freight and passenger traffic, bringing allocation challenges.
- Regional variation: the nationwide nature of this study brings inherent uncertainty due to known regional differences ranging from electricity mixes to infrastructure maintenance and operational procedures.
- EOL: although there is high uncertainty in the EOL processes associated with different vehicles, their impacts on the overall result are very small, and would not change the final results significantly even if increased tenfold.
- Fuel refining: research has shown that different types of fuel (diesel v. jet fuel) require different processes within the refinery. But data are usually bundled, making differentiation amongst fuels difficult.
- Terminals: the exclusion of road and rail terminals presents a source of uncertainty, but this does not affect the overall ranking of modes. This is true as all airport operations, which are more energy intensive than their road and rail counterparts, account for less than 5% of total emissions from air freight transportation.

Parameter uncertainty is associated with LCA input data, and occurs due to imprecise, incomplete, or outdated measurements. The goal is to verify the robustness of the results by analyzing the uncertainty associated with the parameters that contribute the most to the final results. For each transportation mode, the life-cycle phases with the biggest impact on the final result are identified. Within each of these phases, the most uncertain parameters are modified to assess the sensitivity in the final results. Such parameters are chosen based on a methodology adapted from Lindfors

Table 3: Parameter CO_2 elasticities for 10% increase in parameters

	Road		Rail		Air	
	Ranking	Elasticity	Ranking	Elasticity	Ranking	Elasticity
Vehicle Emission Factors	38	0.70	43	0.72	40	0.69
Vehicle Utilization	36	(0.82)	32	(0.70)	36	(0.77)
Average Distance per Shipment	–	–	–	–	32	(0.18)
Vehicle Fuel Efficiency	27	(0.73)	27	(0.70)	27	(0.72)
Vehicle Lifetime (miles)	17	(0.09)	17	(0.01)	30	(0.05)
% of Empty Miles	26	0.16	–	–	26	0.29
Vehicle Maintenance Expenses	–	–	24	0.10	24	0.14
Infrastructure Lifetime (years)	18	(0.08)	18	(0.01)	18	(0.01)
Infrastructure Maintenance Expenses	–	–	24	0.06	–	–
Freight Share of Infrastructure	17	0.10	–	–	17	0.00
Diesel Retail Price	13	0.09	13	0.09	13	0.10

(1995) and Weidema (1996), which enables their scoring and ranking. The latter is normalized to a 0–100 scale, and determines the degree of attention that should be given to a parameter in the uncertainty assessment.

Table 3 presents CO_2 emission elasticities associated with each parameter when it is increased by 10%. For example, when truck emission factors are increased by 10%, final CO_2 emissions for road transportation increase by 7%. As expected, vehicle emission factors are critical parameters, with about 0.7 elasticity for all modes. Vehicle utilization and fuel efficiency are also key factors with even higher absolute elasticities. The remaining parameters have low elasticities, suggesting robustness in the model.

4 Conclusion

This study provides a comprehensive life-cycle inventory of air emissions associated with road, rail, and air transportation of goods in the U.S. It goes beyond tailpipe emissions to include all life-cycle phases of vehicles, infrastructure, and fuels. Results confirm that previous LCAs that accounted for only tailpipe emissions underestimated transportation impacts. In the case of air transportation, differences can go beyond one order of magnitude, depending on the pollutant.

However, the ranking of modes is in line with previous studies of freight transportation modes. If rail CO_2 emissions are taken as a baseline, road and air emissions are 2 and 35 times higher per ton-mile, respectively. It should be emphasized that, should the functional unit be in terms of value transported, the results could be significantly different.

The importance of infrastructure, vehicle production, and pre-combustion processes is confirmed by this study. They will become even more important as new tailpipe emission standards come into place.

Comparison with previous studies also demonstrates the validity of the results. Stodolsky (1998) published different results for the production of trucks and trains due to different assumptions, but both results had the same order of magnitude. As mentioned before, Spielmann (2005) provided the most comprehensive life-cycle inventory of freight transportation, but did not give results in absolute terms. Even though the study is based on European conditions, the contribution of each life-cycle phase for road transportation is similar to the ones calculated by this study. For example, fuel combustion accounts for 70% of life-cycle CO_2 emissions, while the remaining three phases are responsible for 10% each. Spielman calculated 75% for fuel combustion, 5% for vehicles (manufacturing, maintenance, and end of life), 10% for infrastructure, and 10% for pre-combustion. Rail transportation, on the other hand, presents more discrepancies due to the different nature of railways in the U.S. and Europe. While part of the European network is electrified, all U.S. rail freight traffic is run on diesel fuel.

5 Recommendation and Outlook

The uncertainty assessment shows how critical it is to focus on emission factors, vehicle utilization, and fuel efficiency. Future studies should concentrate on all factors influencing these three parameters, including road grade, speed, and vehicle weight. This study is not yet a complete environmental assessment of freight transportation in the U.S. All elements included in the uncertainty assessment should be taken into account in future studies.

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